Blast Vibration and Environmental Loads Acting on Residential Structures: State-of-the-Art Review

D. J. Heath[1]; E. F. Gad[2]; and J. L. Wilson[3]

Abstract: This paper provides a unique literature review of cracking defects developing in low-rise residential structures as a result of deformation caused by environmental loads and low-level blast vibrations. Characteristics of cracking and corresponding causes are reviewed with an emphasis on Australian brick veneer construction although findings are relevant to other construction types around the world. Factors affecting structural response to blast vibrations are examined and loads equivalent to blast vibrations are presented. The influence of expansive soils upon structures is briefly reviewed including a summary of soil shrink/swell behavior. The desiccating effects of vegetation are reviewed in addition to the role trees may play in contributing to damage. The findings of this research are of vital importance to damage investigations in areas experiencing low-level vibrations. **DOI:** **10.1061/(ASCE)CF.1943-5509.0000750.** *© 2015 American Society of Civil Engineers.*

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Introduction

Low-level airblast and ground vibrations are undesirable side effects of blasting in mines and quarries that may reach residential areas causing midwall and whole structure response. Although vibrations are regulated to low levels to avoid annoyance to humans, residents may be startled by a passage of vibrations and become concerned about damage caused to their homes. However, houses are subjected to various loads on a regular basis, which generally go unnoticed. Residents frequently claim damage is attributed to blasting which disrupts and reduces the efficiency of quarries and mines. There are a multitude of environmental and occupant-related loads acting on a structure regularly and irregularly throughout its life either individually or simultaneously. Many areas subjected to low-level blasting are also prone to foundation movement making the task of the investigating engineer even more complex since damage sustained from foundation movement and blast vibrations is frequently attributed to inplane deformation. This paper provides a unique literature review of cracking damage caused to brick veneer without reinforcement (unreinforced) by environmental loads and the effects of low-level blast vibrations and importantly, how these manifest in residential structures.

Defects in Housing

Numerous defects are likely to develop in a house throughout its service life, most of which affect serviceability. In increasing order of severity, damage may be considered to compromise aesthetics, serviceability, or stability [Building Research Establishment (BRE) 1995]. The most frequent encountered performance failure in masonry veneer in domestic construction is cracking which represents an oversight during design and is a symptom of excessive stress, which may be the first sign of a serious defect (Grimm 1997; Page 1993; Sorensen and Tasker 1976; Johnson 2002). Most buildings experience cracks during their service life since it would be uneconomic to design them not to crack (Johnson 2002; Pryke 1982). A structure's tolerance to movement will depend upon the number and size of openings, aspect ratio of wall, the presence of articulation, and the movement profile (Cameron and Walsh 1984). Although commonly encountered defects rarely compromise structural integrity, aesthetically displeasing cracking is considered unacceptable with various socioeconomic costs (Driscoll and Crilly 2000; Page 2001). According to the Building Research Establishment (BRE) the degree of damage that may be tolerated depends on building type, building function, location and nature of damage, user expectations, and the cost of rectification relative to building value (BRE 1995). In addition to being unsightly, cracks permit penetration by rain, water vapor, air, heat, sound, and insects (Grimm 1997). Cameron and Walsh (1984) list the five primary causes of damage in houses associated with foundation movement to be: (1) poor site investigation; (2) improper footing design; (3) poor site drainage; (4) poor workmanship in construction; and (5) insufficient postconstruction maintenance (plumbing, surface drainage conditions, trees too close).

Australian Domestic Construction

The main components of a common residential structure consist of: a load-resisting frame, a roof structure, brick masonry veneer, and a footing system. Each of these are discussed below:

Typically a timber frame is the primary mechanism resisting inplane loads applied to the superstructure. The frame is typically composed of 90 × 35 mm timber studs spaced at between 450 and 600 mm apart with top and bottom plates and noggings (firestopping—lateral bracing) at midheight. Rafters and ceiling joists are attached to the top plate, directly transferring dead and live loads to the structural frame. Inplane loads are resisted by either tension in cross bracing or by membrane action in plywood fastened to the frame. Typical internal cladding is 10 mm

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[1] Research Assistant, Faculty of Engineering and Industrial Sciences, Swinburne Univ. of Technology, Hawthorn, VIC 3122, Australia (corresponding author). E-mail: djheath@swin.edu.au

[2] Professor, Faculty of Engineering and Industrial Sciences, Swinburne Univ. of Technology, Hawthorn, VIC 3122, Australia.

[3] Executive Dean, Faculty of Engineering and Industrial Sciences, Swinburne Univ. of Technology, Hawthorn, VIC 3122, Australia.

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plasterboard. A 40-mm cavity separates the frame and veneer to prevent the transport of moisture.

The roof structure is either a system comprising a frame, beam and rafter configuration, or most commonly, trussed system. Roof cladding is either terracotta or concrete tiles, or metal sheeting.

The masonry veneer comprises extruded clay bricks of dimensions 230 mm (L) × 76 mm (H) × 110 mm (D) in a matrix of mortar containing bed joints and perpend joints having a nominal thickness equal to 10 mm. Steel lintels in the form of angle sections are typically positioned over openings such as doorways and windows. General purpose steel veneer ties are embedded in the mortar and typically fixed to the load resisting frame for the transfer of out-of-plane loads. Veneer ties must not be spaced greater than 600 mm horizontally or vertically; their spacing must be halved at the top of the wall and they must be present within 300 mm of an opening, control joint, or the top of the wall (AS 3700-2001). Weepholes are incorporated in masonry containing flashing to prevent upward movement of moisture and are placed at centers not exceeding 1,200 mm.

The most common choice of footings in Australia is either a concrete slab or concrete strip footings and suspended timber floors, with the former being favored since the introduction of Australian Standard 2870 (Standards Association of Australia 1986). The stiffened raft slab is considered the most economical footing system on relatively flat sites and includes a grid of reinforced concrete subbeams not exceeding 5.0-m spacing for brick veneer [Holland and Richards 1984; AS2870-2011 (Standards Association of Australia 2011)]. The depth of the edge and internal beam may vary from a minimum of 300 mm in depth for soils of low reactivity to 1,100 mm for deep and highly reactive soils. Fig. 1 illustrates a typical stiffened raft slab design.

Overview of Cracking

The primary cause of cracking in masonry walls in Australia is the swelling and shrinkage of expansive soils due to soil moisture changes (Cameron and Walsh 1984). With proper detailing the influence of these causes may be reduced to a point where their effect is not of concern. Defects related to movement may be broken into two groups: internal causes related to the structure and external causes that influence the foundation of the structure (Muniruzzaman 1997; Page 2001).

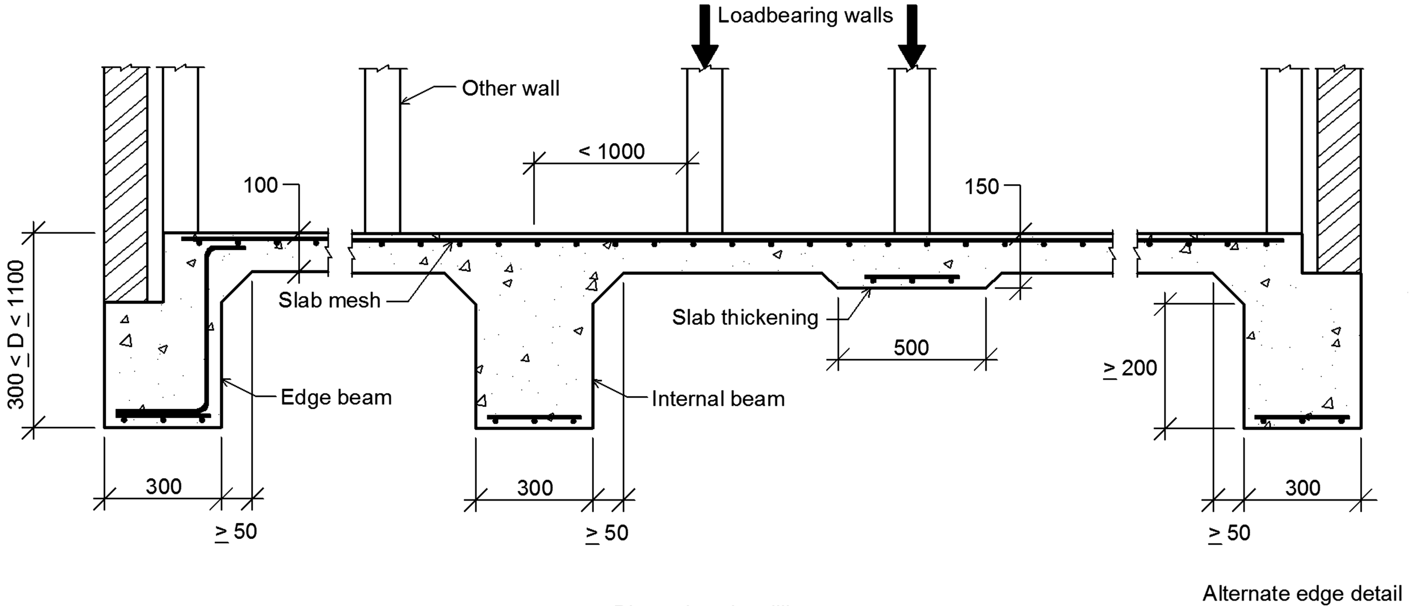
Internal Causes of Cracking

The internal causes of cracking are a result of the behavior of the structure and its interaction with the veneer in isolation of any external causes of cracking such as footing movement. Masonry experiences dimensional changes throughout its life with some being temporary and reversible while others are permanent. In the event of shrinkage being restrained cracks may develop (Zijl et al. 2004; Page 2001). Temporary changes are associated with increases or decreases in moisture and temperature with a corresponding change in the dimensions of masonry although in many cases these effects may be ignored. During hydration of mortar, moisture is consumed and lost to the environment causing the mortar to shrink, which may cause tension cracks (Sugo 2000). In contrast, clay units experience a long-term permanent expansion due to exposure to moisture that may result in cracking. Brick veneer is sometimes plastered with a cement-based product which experiences shrinkage. Poor bond may result in the mortar debonding while a good bond will result in the veneer imposing a restraint, possibly leading to fine cracks developing (Page 2001).

Masonry veneer may become distressed as a result of interaction with other elements such as the structural frame. Thermal movements of such elements and the spreading of pitched roofs may have an influence upon the veneer. Additionally, embedded steel such as lintels may cause distress due to rusting and subsequent swelling if their corrosion resistance rating is inadequate [Clay Brick and Paver Institute (CBPI) 2001].

External Causes of Cracking

External causes of damage to masonry veneer are predominantly associated with movement of the foundation. Movement of reactive clays is the greatest contributor to defects developing in residential structures in Australia. The performance of a building on reactive



Dimensions in millimeters

Fig. 1. Stiffened raft design adopted in common Australian residential construction [adapted from AS2870-2011 (Standards Association of Australia 2011)]

soils depends upon the construction type of the footings and walls and materials used for construction (Cameron and Walsh 1984). Large and concentrated variations in moisture content of reactive soils resulting in either soil shrinkage or heave have the potential to induce severe distress in the structure (Walsh et al. 1976). Although unlikely to ever be experienced, uniform foundation movement over the entire building site would not cause distress to the structure (Sorensen and Tasker 1976). Due to the limited stiffness of the footing system, the effects of swelling or shrinking of the soil will inevitably be transferred to the superstructure. Since the masonry veneer is substantially stiffer than the structural frame the veneer becomes responsible for supporting the resultant inplane loads and acts as a deep beam (Masia 2000). Cameron and Walsh (1984) identify two phases of foundation settlement: (1) moisture egress due to applied pressure from footings; and (2) slip of clay grain-to-grain contact which in severe cases, may continue for centuries.

Natural variations in soil moisture may develop due to factors including seasonal changes in rainfall, solar radiation, and surface runoff due to surface gradients promoting pooling of water close to footings. Soil moisture close to the surface reduces during dry weather and is replenished during wet weather by rainfall and upward migration of moisture from the water table (Page 1998). Artificial disturbances to soil moisture may develop due to excessive garden watering, evapotranspiration due to the desiccating effects of vegetation, and defective services such as water mains, stormwater, and sewerage systems. The desiccating effect of vegetation on soils due to evapotranspiration is also considered an artificial influence on soil moisture in many foundation codes. Defects arising from artificial causes are the manifestation of abrupt changes in soil moisture content although seasonal cycles in weather are the principal cause of movement of the foundations (Sorensen and Tasker 1976). The nature of expansive soil movement has been noted to vary throughout the life of the structure with Meehan and Karp (1994) noting damage begins to appear during the first 2–3 years of age, increases in severity for several years, and then settles into a periodic cyclical pattern.

The vast majority of variations in soil moisture will be confined to the perimeter of the structure, particularly those associated with seasonal effects (Page 2001; Walsh et al. 1976). In reactive soils the shrink/swell mechanism is responsible for the majority of defects experienced in masonry veneer. An adequate prediction of soil movements enables the selection of an appropriate footing system of appropriate rigidity, which will limit deformation and, thus, stress so as not to compromise the strength or serviceability of the structure (Page 2001). If the soil moisture around the perimeter of the structure is relatively uniform but different from the moisture towards the center of the structure a "dishing" or "doming" profile develops in the footings (Fig. 2). During dry periods moisture is released causing reactive soils to shrink resulting in doming. Conversely, wet periods cause soil moisture recharge and in reactive soils upward movement results causing dishing.

A long-term increase in soil moisture inside the edge beam of a concrete slab may also develop which is referred to as center heave. According to Cameron and Walsh (1984), the condition in the middle of the sealed surface will eventually reach equilibrium with the stable soil suction value at depth and may take years or decades. Fityus et al. (2004) reported on a long-term study of the performance of a slab-on-ground situated on highly reactive soil. Shrink/swell cycles were found to influence a very short distance inside the slab edge beam with peak heave developing in 4–5 years after construction while center heave was still rising after 7 years. A similar study conducted earlier by Goode et al. (1984) investigated ground surface profiles beneath four polyethylene surface barriers over expansive shale; two with 2.5 m vertical moisture barriers around the perimeter and two without. One of each type of setup was watered regularly and moisture measurements were made with a neutron probe for 1 year. The vertical moisture barriers were not found to reduce total heave although they reduced differential heave by reducing moisture migration.

Differential settlement has the potential to cause distress to the structure including the masonry veneer. Nonuniform consolidation may develop from poor site preparation, including failure to adequately define the site history. Prior existence of a sealed surface or appreciable vegetation may result in substantial variations in soil moisture across the site creating a predisposition to swelling or shrinkage.

Throughout many regions of Australia blasting is employed to fracture rock in open-cut mines and quarries and has the undesirable side effect of generating airblast and ground vibrations. Airblast is primarily responsible for exciting out-of-plane wall vibration and unlikely to cause damage while ground vibrations primarily cause a racking response with a comparatively greater damage potential. Cracks typically form at stress concentrations around penetrations and propagate diagonally in a similar pattern to subsidence-related cracking, potentially making diagnosis difficult if a preblast condition assessment was not performed.

Other potential common external loads may include subsidence due to underground mining and extreme loading such as a severe storm or earthquake (Page 2001).

Crack Size

The two parameters used to assess cracks are length and width, with peak width being favored to gauge crack severity, particularly from an aesthetic viewpoint. Pryke (1982) defines crack width as the shortest distance between both edges of the crack with the assessment of crack size being conducted in the direction of movement based upon two formerly opposing points, thereby deducing opening and sliding movement. However, a serviceability assessment based upon peak crack width does not necessarily represent the damage state of the wall since secondary cracking may also play an important role including reducing primary crack width

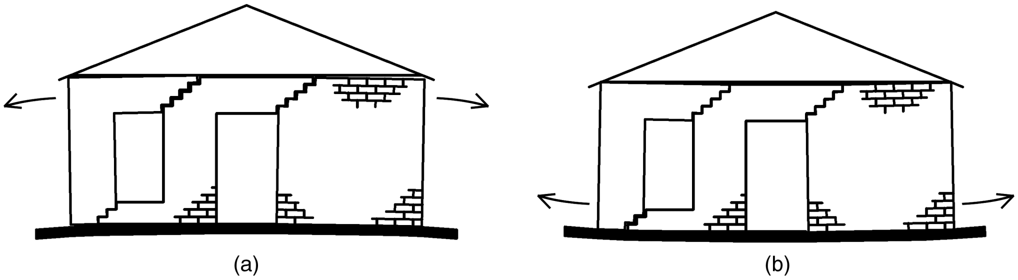

(a)
(b)

Fig. 2. Response of a house to drying around the perimeter (a) doming and wetting around the perimeter (b) dishing

Table 1. Classification of Damage in Walls by Crack Width [Data from AS2870-2011 (Standards Association of Australia 2011)]

Description of typical damage and required repair	Approximate crack width limit	Damage category
Hairline cracks	<0.1 mm	0 Negligible
Fine cracks which do not need repair	<1 mm	1 Very slight
Cracks noticeable but easily filled; doors and windows stick slightly	<5 mm	2 Slight
Cracks can be repaired and possibly a small amount of wall will need to be replaced; doors and windows stick; service pipes can fracture; weather tightness often impaired	5–15 mm (or a number of cracks 3 mm or more in one group)	3 Moderate
Extensive repair work involving breaking out and replacing sections of walls, especially over doors and windows; window and door frames distort; walls lean or bulge noticeably, some loss of bearing in beams; service pipes disrupted	15–25 mm but also depends on number of cracks	4 Severe

(Zijl et al. 2004). This discussion focuses on cracks in masonry veneer although cracks developing within internal finishing and floor slabs are also of concern to homeowners [AS2870-2011 (Standards Association of Australia 2011)]. Separation along the damp proof course is not considered a serviceability failure since this movement is expected in well-designed structures (Masia et al. 2004). The classification of damage with reference to walls is included in Table 1 according to AS 2870-2011 with the severity given a damage category ranking from 0 to 4. The BRE in the United Kingdom originally developed these damage classifications (Tomlinson et al. 1978).

The identification of an "acceptable" crack is contentious and subjective, yet it forms an integral measure for serviceability performance. According to Grimm (1997), cracks should be so small as to be inconspicuous in order to be acceptable. Pryke (1982) suggests people seek professional advice when cracks exceed 3–4 mm in width. Georgiou et al. (1999) note consumers' perception of quality and tolerance to defects is unique to individuals and may not align with those of the builder, creating scope for disputes. Grimm (1997) reports crack widths between 0.25 and 0.38 mm being the limit of acceptability before the appearance is compromised or concern over structure performance develops. Meehan and Karp (1994) agree with Grimm, stating in basic terms, a "significant" crack has a width in excess of about 0.4 mm. According to BRE (1995), aesthetic damage falls in the damage category range from 0 to 2 as per Table 1, consistent with the greatest objectionable crack widths reported in the literature. Masia et al. (2002) state width is the most concerning feature of a crack rather than its location while Page (2001) notes there is no single correct answer due to the number and complexity of factors influencing occupant response and that it is uneconomical to avoid cracking completely. The building type, wall type, location in wall, and surface finish are all important measures affecting crack severity in addition to direct measurement. Furthermore, the ease of repair is an important consideration, with increasing crack widths signaling rectification work beyond the scope of repointing of mortar (Table 1). For damage category 1 or 2 simple measures to stabilize soil moisture are recommended as part of normal house maintenance while more serious attention is required for damage categories 3 and 4 [AS2870-2011 (Standards Association of Australia 2011)]. A 1-mm crack passing through mortar joints in brick veneer will be far less noticeable than the same crack passing through a plastered finish (CBPI 1999). Grimm (1997) states crack widths less than 0.1 mm to be insignificant since wind-driven rain will be unable to enter.

Patterns of Cracking in Masonry

Cracks develop in masonry due to tension and provide a natural articulation joint allowing stress relief. The nature of a crack contributes to rigid body movement of the masonry and, thus, influences the response to external effects (Muniruzzaman 1997). Sorensen and Tasker (1976) provide an excellent summary of the types of cracks likely to be experienced in masonry from uneven settlement of foundations. However, the variability of masonry may also influence crack patterns with factors such as localized regions of poor bond and precracked units influencing the direction of crack propagation (Muniruzzaman 1997). The inherently low unit/mortar bond creates a tendency for cracks to pass through joints rather than through units (Page 2001). The point of crack initiation and direction of propagation are both influenced by the presence of penetrations, which introduce stress concentrations at their re-entrant corners. Johnson (2002) also suggests a complete understanding of cracking requires knowledge of whether crack movement is static, cyclic, and/or progressive. Corners and offsets are also vulnerable to cracking (CBPI 2001). Owing to these complexities, the prediction of crack width is not deterministic (Page 2001).

Cracks caused by uneven foundation settlement are generally diagonal or vertical, although they may take any form (Grimm 1997; Sorensen and Tasker 1976). Similarly, Page (2001) notes distress attributed to the effects of dishing or doming may appear as diagonal or vertical cracks depending on wall geometry and the existence of penetrations. External causes of cracking result in tapered cracks suggesting a bending failure whereby the wall on one side is rotating away from the other (Muniruzzaman 1997; Sorensen and Tasker 1976; Pryke 1982). Cracks developing from external causes may originate at the top or bottom of the wall or at the corners of penetrations. Muniruzzaman also notes horizontal cracks may develop due to movement of the foundation. Cracks are commonly experienced at the connection between an existing structure and an addition due to differential movement attributed to different foundations. Under this condition vertical cracks are normally encountered at the relatively weak interface although cogged cracks are likely when a masonry addition has been keyed into the existing structure. For these reasons an articulation joint is recommended at this location.

Horizontal cracks may develop due to a number of different causes, most of which are classified as internal causes discussed previously. Cracking due to brick growth is likely to induce vertical cracking, particularly close to corners of walls, which may also cause oversailing of upper portions of a wall over lower parts (Page 1993). Parapets are particularly prone to the effects of brick growth due to greater exposure to moisture and limited restraint. Brick growth may also lead to various distortions in walls, which may cause bowing and arching and disturbance to the operation of doors and windows (Page 1993).

Damage Studies of Residential Structures

Holland and Richards (1984) investigated over 2,000 distressed houses and reported sticking of doors and windows to be the greatest annoyance to occupants and suggested warnings should accompany economical footing designs regarding consequences of poor site maintenance. Longworth et al. (1984) observed a 30-mm subsidence over a 6-month period in a house following the removal of a leaking tap on expansive clays while Domaschuk et al. (1984) measured 100 mm differential movement during a 3-year monitoring period of 180 houses having shallow footings on expansive clays. Crilly (2001) examined 484 cases of subsidence-related damage in the United Kingdom and found 68% of cases were attributed to trees with approximately 76% of cracks being between 1 and 15 mm with 50 years being the average time to perception from construction. Page and Murray (1996) inspected 501 residences in the United Kingdom and found approximately 64% of causes of structural defects were attributed to movement of reactive clays. Leach et al. (1995) conducted inspections of 80 houses on extremely expansive soils in Adelaide, South Australia. Barthur et al. (1996) later extended the survey by investigating 216 articulated brick veneer and articulated solid brick residences on stable to highly reactive soils. Footing sizes stipulated in AS2870-1988 were found to be nonconservative with a 50% probability of crack width exceeding 1 mm.

Effects of Blast Vibrations on Residential Structures

Purpose and Characteristics of Blasting

Blasting is employed in mines and quarries as the most efficient method of rock fragmentation although 20–30% of explosive energy is unavoidably lost which becomes responsible for disturbance to neighbors. The location of mines and quarries are unavoidably in close proximity to residential areas in many regions throughout Australia and the world.

Controlled blasting techniques are employed to maximize efficiency of blasting while minimizing disturbance to neighbors (Singh and Singh 2005; Sharma 2008). Surface mines typically detonate between 90 and 3,200 kg of explosives per delay with more than 100 t of explosives in total, creating considerable potential for the generation of airblast and ground vibrations (Crum et al. 1992). Beyond the zone of fragmentation the strain energy becomes ground vibrations that may propagate many kilometers at perceptible levels. The two factors having the greatest influence upon the ground vibration waveform are geology of the propagating medium and timing (delay) between charges in a detonation sequence.

Propagation of Blast Vibrations (Airblast and Ground Vibrations)

Surface waves propagate along the surface and include vertical and horizontal shear waves denoted as "S" waves, compression waves denoted as "P" waves, and Rayleigh waves denoted as "R" waves. A Rayleigh wave is the most important for structural response and is responsible for longitudinal and transverse movement of particles relative to the direction of propagation. Body waves are transmitted deeper into the rock and soil and are comparatively smaller in amplitude and higher in frequency relative to surface waves (Crum et al. 1992).

The absorption of energy is a function of the material's deformational properties; thus, the decay in amplitude becomes a function of energy loss per cycle (Dowding 1996). Higher frequency P and S waves decay much more rapidly than R waves which are substantially lower in frequency. Additionally, the energy of an R wave spreads cylindrically rather than spherically like body waves. Consequently, at large distances from the blast R waves dominate ground particle motion since they have experienced fewer deformational cycles compared to the higher frequency P and S waves. Further, a separation develops between wave types at large distances since P and S waves travel more rapidly than R waves through a given media (Dowding 1996). Vibrations from blasting in coal mines typically have a trailing large-amplitude and low-frequency wave compared to vibrations generated from quarry blasting (Siskind et al. 1980). Hence, vibrations from coal mine blasts have lower principal frequencies possessing greater damage potential due to their similarity with natural frequency of residential structures (Konon and Schuring 1983).

Modes of Structural Response

The factors of interest in the study of the response of structures to blast vibrations are the characteristics of blast-induced ground motions, dynamic response of structures, and the threshold of response at which a structure will crack (Dowding and Murray 1981). Blast vibrations exciting structural response are transmitted via the walls and roof in the case of airblast and through the footing system in the case of ground vibrations (Eltschlager 2001). Ground vibration is typically reported with a peak component velocity (PCV) in units of millimeters and airblast is typically reported as a pressure above atmospheric with units of dB. Following a disturbance to a structure, a response will develop at one or more of the structure's natural frequencies (Sharma 2008). The impulsive pressure loading from airblast predominantly generates midwall response whereby walls, ceilings, and floors vibrate perpendicular to the plane of the building component (Aimone-Martin et al. 2003). The midwall response is generated at higher exciting frequencies than whole-structure response and is only audible due to rattling of doors and windows and loose objects attached to walls. The range of airblast frequency responsible for exciting midwall response is about 10–25 Hz (Siskind et al. 1980) with the amplitude of response typically being four times greater than the response generated by the accompanying ground motions (Dowding 1996). The audible component of airblast perceived by humans as sound or noise has negligible effect on structure response. Ground vibrations are predominantly responsible for generating a racking response or whole-structure response whereby shear strains are generated in walls due to the horizontal translation of the top of the wall relative to the bottom. A lower frequency excitation is required to excite superstructure motion, which includes racking and torsional distortion of the structural frame. Whole-structure distortion is much smaller than midwall distortion. Fig. 3 illustrates these two primary responses.

From a study of 76 houses subjected to 219 production blasts, Siskind et al. (1980) noted a racking response generated by a 12.5-mm/s ground vibration was equivalent to a 137–138 dB airblast level while a midwall response generated by a 12.5-mm/s ground vibration was equivalent to a 128–130-dB airblast level. Stagg et al. (1984) investigated strains in gypsum wallboard due to airblast and ground vibrations and found a 132-dB airblast generated equivalent strains to a ground vibration of 25.4 mm/s. Airblast is therefore much less likely to be responsible for cracking damage in walls with windows considered the most susceptible element to damage (Rainer 1982; Shaw 1989; Nicholls et al. 1971). Further, the racking distortion provides the greatest indicator of cracking potential in structure response (Siskind et al. 1980; Singh and Roy 2008).

Characteristics of Blast Vibration Affecting Structural Response

The characteristics of a blast vibration having the greatest influence on structural response are duration, amplitude, and relative match between the natural frequency of the structure and the dominant frequency of the incoming vibration (Singh and Roy 2010). A structure's characteristics of dynamic response, namely the natural frequency and damping values, determine its tolerance to incoming

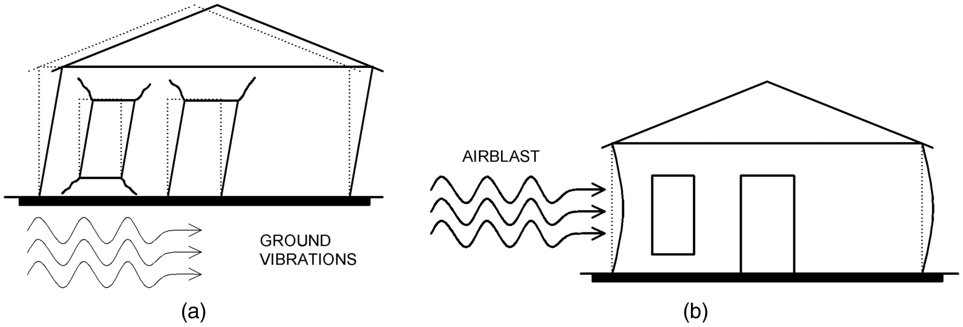


Fig. 3. Structural response to blast vibrations: (a) racking; (b) midwall

vibration (Konon and Schuring 1983). However, the response is much more sensitive to changes in natural frequency compared to changes in damping (Siskind et al. 1980). It therefore follows that the amplification of ground vibration in the structure depends on the structure's damping coefficient and the amount of energy in the ground vibration's frequency spectrum near the natural frequency of the structure (Singh and Roy 2010). The typical dominant frequency range of blasting from quarry and coal mining is in the range of 10–40 and 5–25 Hz, respectively.

Dynamic Characteristics of Residential Structures

Medearis (1977) reported structure frequencies in the range of 4–18 Hz and median damping to be 5.2% from a study of 63 residences. Siskind et al. (1980) measured structure natural frequency to range from 4 to 12 Hz, 5% was considered a good approximation of critical damping and amplification factors were 1.5 on average although as high as 4.0. Dowding and Murray (1981) reported a range in natural frequency of 23 single and double-story structures to range from 3 to 11 Hz and percent of critical damping ranging from 2 to 23% with an average of 4.6% with some structures requiring moderate to extensive repair. Aimone-Martin et al. (2003) investigated 25 structures and noted amplification factors up to 3.3 for dominant frequencies of vibration greater than 7.1 Hz while amplification factors up to 5.0 were observed for vibrations having a lower dominant frequency. Singh and Roy (2008) observed natural frequencies ranging from 7 to 14 Hz in single and multistory residential structures in India; in similar structures, Singh and Roy (2010) noted structure natural frequencies to range from 6.0 to 14.8 Hz with damping being 2.1–10.9% of critical and amplification factors up to 5.2. The greatest amplification ratio reported was 6.0 by Siskind and Stagg (2000) who monitored 11 houses of nonstandard construction and atypical vibration frequency signatures.

Level of Vibration Causing Threshold Damage

The susceptibility of a structure to damage depends on vibration levels, excitation frequencies, and factors relating to the site and structure (Singh and Roy 2010). Importantly, the threshold level of cracking is highly dependent on the level of residual stresses present that may reduce the apparent PCV level causing damage. It is widely accepted among blast researchers that the lengthening of old cracks and formation of superficial "hair-sized" new cracks constitutes a threshold damage level (Rainer 1982; Northwood et al. 1963; Singh and Roy 2010; Siskind et al. 1980; Stagg et al. 1984; Dowding 1996). Few publications present observations of damage and corresponding ground motion measurements. Dowding (1996) notes the only definitive method of correlating the incidence of cracking with blast vibrations is to conduct a pre- and postvibration crack survey, which will also reduce complaints and lawsuits. The identification of an appropriate limit unlikely to cause any damage is made all the more difficult by the presence of residual stresses in components of structures, particularly older structures, resulting from settlement, poor maintenance, weather cycles, and prior repair and renovation (Konon and Schuring 1983). For this reason, Siskind et al. (1980) note there may be no absolute minimum vibration damage threshold whereby blasting or environmental or occupant-related vibration could precipitate a crack. However, Aimone-Martin et al. (2003) note no damage has been reported in the literature below a ground vibration level of 12.7 mm/s although most researchers have reported much higher threshold PCV's for the onset of damage. Stagg et al. (1984) also constructed a structure near coal mine blasting and examined its response to blast vibrations increased from 2.5 to 176 mm/s. Corner crack extensions in gypsum wallboard were observed after 22.4 mm/s ground vibrations, cracks in wallboard taping developed after 45.7 mm/s vibrations, and cracks in masonry walls first developed following a vibration with PCV = 86.4 mm/s. Gad et al. (2005) monitored the response of a house to progressively increasing blast vibrations. The first increase in the length and width of an existing crack did not develop until the structure experienced a 70-mm/s blast. Heath et al. (2008) subjected a single-room brick veneer house to progressively increasing blast vibrations and while tie loosening developed at PCV = 70 mm/s, the onset of visible cracking was not detected until the intensity of vibration was increased to PCV = 127 mm/s.

Effect of Fatigue on Structures from Blasting

Fatigue becomes a problem if a given value of stress is exceeded consistently. However, a reduction in the ultimate stress develops only after many thousands or possibly millions of loading and unloading cycles. Stagg et al. (1984) conducted fatigue testing of a timber-framed house using two mechanical shakers. After 56,000 cycles (equivalent to 28 years of blasting based on two production blasts per day) simulating a 12.7-mm/s ground vibration, first threshold cracking developed in a taped wallboard joint and joint compound over a nail head. The first crack in a joint of the structure's brick veneer was observed after 229,500 cycles that included an initial 200,363 cycles of 12.7 mm/s shaking and 29,137 cycles of 7.6 mm/s shaking. Siskind et al. (1980) reported on shake table fatigue tests of a 2.4-m by 2.4-m timber-framed, gypsum-wallboard clad single-room structure. The structure was excited horizontally and vertically with a gradually increasing shaking intensity. First deterioration of the wallboard occurred after 2,670 simulated blast events with a greatest shaking level of 101.6 mm/s achieved. These studies suggest the effects of fatigue are insignificant for regular blasting activities.

Comparison of Wind Loading with Blast Loading

Siskind and Stagg (2000) investigated structural response to the influence of wind and found a 100-km/h wind speed was approximately equal to the structural response generated from a PCV = 33.4 mm/s vibration while the structural response from a 177-km/h wind speed was approximately equal to a PCV = 103 mm/s blast vibration. Aimone-Martin (2005) measured a 0.007-mm change in crack width due to a wind gust equal to 54.8 km/h while a PCV = 14.2 mm/s vibration generated a 0.006-mm change in crack width. Aimone-Martin et al. (2003) examined the response of trailer homes to wind response and found from wind speeds up to 51.6 km/h the greatest racking response was equivalent to only PCV = 1.4 mm/s. It may therefore be seen that wind gusts from a strong storm event will generate a structural response exceeding that likely to be experienced from blast vibrations within vibration limits.

Influence of Temperature and Humidity

Aimone-Martin (2005) examined the response of two residential structures to temperature and humidity and found close correlation between the diurnal cycles in humidity with crack movement. The greatest daily change in crack width was 0.17 mm which was 72 times greater than the response measured from a PCV = 14.2 mm/s vibration. Waldron (2006) observed temperature variations generated changes in crack width that were 120 times greater than the peak dynamic crack response due to a PCV = 4.3 mm/s vibration. Rosenhaim (2005) monitored changes in exterior stucco cracks and measured peak dynamic crack motion to be 0.07 mm for ground vibrations up to 9.3 mm/s while peak changes in crack width attributed to environmental effects were equal to 0.12 mm. Gad et al. (2005) monitored the response of a house over time to environmental phenomena and measured a 0.7-mm crack closure attributed to foundation swelling while a 190-mm/s blast vibration reduced the width of the same crack by 0.3 mm. Dowding (1996) reported on a house examined for its response to environmental loads and blast vibrations where weather-induced changes in crack widths exceeded changes in crack width attributed to a 19-mm/s vibration by a factor of 3.5. It is therefore apparent houses are frequently subjected to weather-related deformation far exceeding deformation attributed to blasting levels capable of causing annoyance.

Occupant Loads in Residential Structures

Occupant-related loads are generally transient and applied locally rather than to the whole structure; they may develop an appreciable structural response and occur frequently. Aimone-Martin et al. (2003) examined structure response to occupant loads when investigating the response of various types of structures to blast vibrations. Typical occupant activities generated whole-structure responses up to approximately 13.0 mm/s while midwall response measured a peak of approximately 54.4 mm/s. The response was equated to the effect of a 7.1-mm/s ground vibration on a single-wide trailer structure and 2.8 mm/s for a single-story adobe house. Nicholls et al. (1971) investigated occupant-related activities including walking, door closing, jumping, heel drops, an automatic washer, and clothes dryer. Jumping generated the greatest local peak with PCV ≈ 130 mm/s in the room of the activity and was considered potentially damaging. Structural response generated from the mechanical devices was likened to the response expected from typical quarry blasts. Siskind et al. (1980) investigated human-produced transient loads in a dwelling with the investigation including jumps, heel drops, door slams, nail pounding, and walking. Results of the study revealed strains measured over penetrations were comparable with those expected from ground vibrations up to approximately 12.7 mm/s. It was also found that in contrast to the findings of Nicholls et al. (1971), localized occupant loads were found to have the potential to produce considerable strains in distant parts of the structure. The study performed by Stagg et al. (1984), which examined the performance of a timber-framed structure to environmental and blast vibrations, also investigated the response to occupant loads including walking, heel drop, low jump, high jump, door slam, sliding door slam, and nail pounding. Strains recorded from the study were compared with strains measured on the same structure to vibrations up to nearly 160 mm/s. Further, a glass door slam was found to be comparable to a 13.0-mm/s vibration while nail pounding was considered equivalent to a 23.4-mm/s vibration.

Causal Mechanisms of Foundation Movement

Differential movement of foundations may be caused by numerous factors with one or more contributing at any given time. Page and Murray (1996) report on a survey of 501 properties in East Midlands, U.K., identifying 844 specific structural defects. The survey revealed 63.9% of defects were attributed to ground movement, 22.4% to the superstructure, and 13.7% were associated with material defects. Sorensen and Tasker (1976) list the principal causes of movements in foundations to be: settlement, moisture variation in plastic soils, instability of sloping ground, and miscellaneous factors. Settlement has been defined as the "sinking of a building due to the compression and deformation of the underlying soil" (Terzaghi et al. 1996). Page (2001) notes differential settlement may result from nonuniform consolidation, the existence of variable ground beneath the structure, and/or a local failure of the foundation. Depending on soil permeability, the duration in which settlement occurs from the time of construction is generally 2–3 years (Pryke 1982). Since settlement is a function of load on the foundations and soil characteristics, which generally remain the same throughout the life of the structure, further discussion of this mechanism will not be made. The process of settlement is well understood and is covered extensively in the literature (Terzaghi et al. 1996; Craig 2004). The remaining categories are covered in the following subsections.

Soil Moisture Variation

All five continents contain expansive soils with construction being influenced in Israel, United Kingdom, India, United States, South Africa, and many other countries (Driscoll 1983). In Australia, approximately 20% of soil is estimated to be reactive in nature (Richards et al. 1983). Crilly (2001) states that shrinkage and swelling of reactive soils is the greatest contributor to foundation-related damage. Damage to structures in the United States attributed to expansive soils is greater than damage caused by natural catastrophes such as cyclones, earthquakes, and landslides (Barthur et al. 1996). The shrink/swell characteristics of a soil are dependent not only on soil type but also on climate, with semiarid regions being more prone to deep-seated variations in soil moisture and, thus, larger heaves. The characteristics of reactive soils leading to potential for volumetric change are beyond the scope of this paper with comprehensive explanations provided elsewhere (Chen 1988; Terzaghi et al. 1996; Craig 2004).

While reactive soils increase in volume with water ingress and reduce in volume with water expulsion, several important factors influence the magnitude of this volumetric change. Sorensen and Tasker (1976) note the principal contributor to soil moisture change is seasonal change in rainfall. Pugh (2002) shares this view and investigated the correlation between subsidence insurance claims in the United Kingdom and rainfall deficits. Clear surges in subsidence were evident following the drought periods of 1975 to 1976, 1983 to 1984, 1988 to 1992, and 1995 to 1997, with the base level of claims increasing from 1,000 in 1976 to 38,000 in 2000. Drying of soil develops by solar radiation, particularly regions of the structure receiving greater amounts of sunlight (Sorensen and Tasker 1976). Page (1998) reports extended dry periods may lead to differential settlement resulting from the removal of fine material from granular soils caused by a drop in the water table.

Vegetation has the capacity to cause considerable localized desiccation of soils that in the vicinity of structures may lead to differential foundation movement. The problem of water abstraction caused by the presence of vegetation adjacent to structures is well established as a global issue (Holtz 1983; Cutler and Richardson 1989; Williams and Pidgeon 1983; Richards et al. 1983; Ravina 1983). Page and Murray (1996) found tree shrinkage contributed to 51.1% of damage cases involving volume changes in reactive soils. Owing to the importance of vegetation-related subsidence the subject will be covered in greater detail below.

Reductions in soil moisture may have detrimental effects on structures although increases in soil moisture with corresponding volumetric expansion of the soil may have equally damaging effects. The CSIRO (2003) report leaking pipes and defective roof plumbing as lead causes of localized saturation of soil adjacent to footings and that pervious backfilled trenches may become watercourses to channel water to foundations. Page and Murray (1996) reported on a defect survey from which it was found leaking sewers contributed to approximately 31% of structural defects associated with ground movement. Leaking services may be the cause or consequence of subsidence or heave (Hunt et al. 1991). Excessive watering may also lead to heave of reactive soils and in some cases to a loss of bearing capacity (Sorensen and Tasker 1976). Fityus et al. (2004) investigated natural moisture migration toward soil beneath impervious covers such as reinforced concrete slabs. The net result is heave beneath the center of the building with the potential to develop dishing or doming profiles caused by regular fluctuations in soil moisture content at the periphery of the foundation (Page 2001). Restoration of soil moisture from an existing deficit resulting in swelling of soil is a problem that has also caused considerable damage to structures and is mainly a problem when a structure is built on a site shortly after a tree of appreciable size has been removed (Biddle 1998).

Miscellaneous Factors

There are many potential contributors to foundation movement that do not involve a shrinking or swelling of reactive soils. Erosion in noncohesive soils is one such cause that may be exacerbated by certain chemicals leading to cavities or large vibrations from traffic or machinery (Bullivant and Bradbury 1996; Shabha and Kuhwald 1995). However, Page and Murray (1996) note densification from vibration is very rare. Certain areas may be prone to temporary or permanent subsidence caused by underground mining which may persist for many years after mining has completed (Grimm 1997; Hunt et al. 1991; Shabha and Kuhwald 1995; Dickinson and Thornton 2004). A nearby excavation may lead not only to a loss of lateral support causing lateral expansion and subsidence but also a reduction in soil moisture content by solarization and a localized drop in the water table (Page 1998; Freeman et al. 1994). Residential areas may exist on slopes steep enough that gravity is an important consideration in the stability of the soil which may be further exacerbated by high soil moisture (Sorensen and Tasker 1976). More comprehensive descriptions of factors affecting slope stability may be found in geotechnical references such as Terzaghi et al. (1996) and Das (2005).

Influence of Vegetation

Vegetation contributes to the urban environment, having aesthetic and environmental appeal as well as providing shade and adding value to properties. The primary relevance of vegetation in damage studies is their moisture demand. While regular variation in soil moisture is normal, vegetation can increase the range of moisture content, which in the presence of structures and expansive soils may cause damage (O'Malley and Cameron 2005). The primary factors influencing the environment in the vicinity of a tree are discussed in this section.

Structure of a Tree

All plants attempt to expose their foliage to sunlight to promote growth, with trees being more competitive due to their ability to grow a trunk structure. The two main elements within the structure of the plant are the phloem that is the innermost layer of the bark structure and the xylem that lies beneath the bark and is responsible for transporting water from roots to the leaves. The leaf is the primary photosynthetic organ that reduces atmospheric carbon dioxide into carbohydrate using light energy causing a parallel release of oxygen from water (Kozlowski and Pollardy 1997). Each leaf contains millions of tiny pores called stomata that regulate the release of moisture, with the number of stomata being related to water demand of the tree. Since the entire system from leaf to roots is continuous, the suction developed at the leaf is proportional to the suction occurring in the roots. Hence, pruning causes an immediate reduction in moisture demand as the tree attempts to maintain a constant root:shoot ratio (Biddle 1998). For deciduous trees, the absence of leaves causes extraction of moisture from the soil to cease completely. Conversely, maximum suction is developed when foliage growth is complete. Evergreen trees continue to extract water from the soil during winter although the quantity is considerably reduced.

Root Network

Biddle (1998) identifies four main functions of the root system: (1) provide support and anchorage, (2) absorb water, (3) absorb nutrients for growth, and (4) as a storage organ for starch. While there are a few main roots near the trunk of the tree intended for structural support, the remaining root structure is optimized for the extraction of water and nutrients. The lateral and vertical distribution of roots is determined by the availability of water, not the shape of the crown. Garden variety trees have root networks rarely exceeding 1.0 m in depth with the majority growing within the top 0.5 m (Biddle 1998). Knight (1999) reported on dimorphic root systems present in mature trees whereby the lateral network of roots collected moisture available close to the surface whereas deep-seated moisture was sourced through vertical sinker roots. A well-drained soil promotes deep root growth while heavy clays encourage shallow root systems, penetrating to about 1 m (Cameron 1985). Due to the competition between the trees, root systems tend to be more extensive when trees are planted close together. Roots are opportunistic, although they will only enter service pipes if they are defective. Pavements provide another opportunity for root growth as the wet environment encourages a proliferation of roots immediately adjacent to paving as they take advantage of the moisture (Cameron 1985). Roots are often found near service pipes since the permeability of backfilled trenches is generally high and they are attracted to the condensation often forming on pipes that are cooler than the surrounding soil.

Effect of Vegetation on Soils and Zone of Influence

Soil experiences seasonal movement caused by increases and decreases in moisture content which is influenced by evaporation from the soil surface, transpiration from vegetation, and drainage of water within the soil (Biddle 1998). The presence of vegetation exacerbates this natural cycle by the combination of high-photosynthetic activity and low rainfall during warmer months, followed by low-moisture demand and higher rainfall during the winter period. In the presence of vegetation of appreciable size, transpiration is by far the greatest contributor and leads to soil moisture deficit causing surface movement in expansive clays making certain species inappropriate in a suburban environment (Cameron et al. 2006; Holland and Richards 1984).

One of the earliest efforts to investigate the spread of roots was the Kew Root Survey, which ran from 1971 to 1979 in the United Kingdom (Cutler and Richardson 1989). Approximately 2,600 records of trees were obtained which detailed the spread of tree roots and the environment in which they were growing. The BRE, also in the United Kingdom, created a subsidence database with Crilly (2001) reporting on trends from 484 records of subsidence where trees were implicated in 82% of all cases.

Owing to the ease of measurement, tree height has traditionally been used for the identification of "safe distances" for trees near structures such as the tree risk ranking provided by BRE Digest 298 (Driscoll and Crilly 2000). However, the simplicity of this approach has drawn considerable criticism (Biddle 1983; Cutler and Richardson 1989; Freeman et al. 1994; Biddle 1998). Bullivant and Bradbury (1996) provide a table of appropriate spacing between different tree species and a dwelling but suggest a safe distance of at least 20 m could be adopted. Cutler and Richardson (1989) supplemented data from the Kew Root Survey with data from 11,000 tree roots and 2,300 shrub roots and provided graphs of the percentage of cases of damage versus distance to the implicated tree. However, the tree-to-structure safe limits have been criticized with soil reactivity and species-specific moisture demand not being addressed (Freeman et al. 1994; Dickinson and Thornton 2004). Biddle (1998) provides a comprehensive examination of the desiccating effects of trees with common species being ranked in order of propensity to cause damage. Tables developed by the National House-Building Council (NHBC) of the United Kingdom for safe tree-to-structure distances are referred to which account for soil plasticity, tree water demand, and broad-leafed foliage.

While the potential to cause damage by trees is highly variable due to a number of factors, various authors have investigated the lateral reach of trees. Williams and Pidgeon (1983) suggest a tree's root structure may be approximated from the structure of its crown and similarly, Kramer and Kozlowski (1960) state isolated trees affect the ground from 1 to 1.5 times their height while Cameron (1985) suggested a lateral spread of roots to be 0.4 to 2 times mature tree height meaning an even greater zone of desiccation develops due to suction. Knight (1999) concluded root systems would follow moisture gradients up to a distance of 20 m while Richards et al. (1983) noted roots from a row of 25-m high pine trees were found 47 m from the trees.

The depth of desiccation is of great importance for structures with shallow footings. If soil moisture recharge is less than drying a zone of permanent desiccation may develop. According to Cameron (2001) the influence of trees on soil suction is minimal close to the surface but tend to increase drying at depth in semiarid environments. Ravina (1983) noted deep-rooted plants cause desiccation up to depths of 3 m while Freeman et al. (1994) suggest a much greater depth of 6 m or more is possible. Australian native species of vegetation can tolerate greater soil suctions compared with exotic species although they use more water if available causing rapid desiccation in the dry season (Richards et al. 1983). Hence, the response of roots to depletion of moisture in soil depends on the hardiness of the species (Cameron 2001).

Comparative Effects of Shrubs and Grasses

Shrubs and grasses may cause comparable desiccation to larger vegetation albeit to lesser depths. Cutler and Richardson (1989) suggest a single small shrub will be unlikely to desiccate soil sufficiently to cause damage but noted shrubs are frequently planted together such that the combined effect may be potentially damaging. Biddle (1998) states a particularly damaging scenario is a line of shrubs or a hedge in close proximity to a wall since a wall is generally only capable of spanning the desiccated area of a single shrub. Lawns and grasses reduce runoff and contribute to desiccation during drier periods (Holtz 1983). Knight (1999) noted grasses in temperate zones reach to a depth of up to 2.4 m although 83% of root mass lies within the top 0.3 m of soil. Richards et al. (1983) measured suction changes under grassed areas in South Australia to depths of 1.4 m with soil suction measured to be approximately 1.6 MPa close to the surface.

Heave and Recovery

According to Driscoll (1983), a significantly desiccated soil is capable of lifting a low-rise building upon rehydration. Heave is the term used to describe the restoration of moisture in soil beneath buildings constructed on a preexisting deficit at the time of construction (Biddle 1998). Careful consideration of heave potential is required if tree removal is to be undertaken so as not to enhance damage, especially if the tree is older than the structure (Freeman et al. 1994). If the tree is younger than the structure removal is suggested with long-term recover of the soil sometimes taking many years resulting in gradual closure of cracks.

Controlling Water Demand of Trees

Action taken to combat the effects of vegetation in the vicinity of structures varies. Traditionally, felling has been favored with the belief pruning encourages tree growth (Driscoll and Crilly 2000; Bullivant and Bradbury 1996). However, Cameron and Walsh (1984) suggest the decision should be based upon consideration of the tree's proximity to a structure and the level of damage attributed to the tree. Where a "severe" level of damage has been sustained, trees within three-quarters of their height to the building may be removed as an appropriate treatment. Action required for a "low" damage level could include either tree removal if the tree's proximity is within one-third of its height to the building or regular canopy pruning and installation of soil water reservoirs. One of the greatest deterrents against pruning is the ongoing commitment and costs with a study conducted by the Horticulture LINK Project 212 in the United Kingdom finding a 70–90% crown reduction was necessary to reduce desiccation by trees (Hortlink 2004).

Controlling root systems has proven effective in reducing the drying effects of trees. Root severance is one method to control moisture demand although it is important an impermeable barrier of sufficient size is installed to avoid roots growing around and below the barrier (Freeman et al. 1994). Biddle (1998) suggests the barrier should extend from the surface to a depth of 3 m. Cameron and Walsh (1984) recommend the installation of a 1.5-m deep concrete wall 150 mm thick adjacent to a house where damage to a structure caused by a tree is "moderate" to "severe." The barrier is intended to redistribute and equilibrate soil moisture by isolating the structure from factors in the surrounding environment influencing surface moisture. However, this is only recommended in severe cases if underpinning is undesirable and tree removal cannot be performed. Where slight damage to a structure is attributed to desiccation caused by a tree, regular watering is recommended below the drip line (outer perimeter of canopy).

A commonly referenced principle for minimizing damage to structures from trees is to ensure a satisfactory separation using the distance-to-height ratio (D:H). CSIRO (1991) suggests the type of vegetation should be selected according to its size and intended proximity to a residence. Many foundation codes such as AS2870-1996 assume the distance between tree and structure is sufficiently great that the presence of the vegetation will not influence the design site movement. The minimum ratio reduces with reducing soil reactivity, from D:H = 1.5 recommended for extremely reactive sites to D:H = 0.75 for moderately reactive sites. These recommendations are valid for typical domestic structures on shallow footings. Cameron and Walsh (1984) suggest damage to structures was unlikely for D:H ratios exceeding 1 for a single tree and 1.5 for a row of trees. However, the general trend in cities around the world is for reduced allotment size and increased dwelling size such that adherence to D:H guidelines would result in a treeless urban environment (Cameron et al. 2006).

Conclusions

Various types of defects are expected to affect residential structures throughout their design life. The most frequently reported defect is cracking and while rarely affecting structural stability, it is considered to degrade aesthetics and serviceability and is often costly to repair. The most frequent reported cause of cracking is shrinkage and expansion of reactive clays, which has the greatest effect along the perimeter of raft footing structures. Artificial wetting exacerbates seasonal variations in soil moisture content or drying caused by factors such as leaking services, excessive garden watering, poor surface drainage, and closely located vegetation. The design of Australian house footing and wall systems is partly based on the premise occupants will tolerate crack widths up to 5 mm in width although crack widths from 0.25 to 4 mm have been reported as the limit of acceptability. This discrepancy leads to complaints requiring potentially costly investigations and remedial work.

Disruption of the moisture content of expansive soils features prominently in damage studies of residential structures and while vegetation is most frequently implicated in damage, poor site maintenance is also commonly reported. However, assumptions in foundation codes, such as AS2870-2011, regarding proper maintenance are not being followed giving homeowners false expectations.

Blasting in mines and quarries to fracture rock is employed in Australia and around the world. Nearby residential areas are subjected to low-level vibrations with a racking response predominantly caused by ground vibrations posing the greatest damage potential. Owing to numerous influencing factors, an indicative vibration level corresponding to the onset of damage in houses is yet to be identified although no damage has been reported in the literature at ground vibration levels below PCV = 12.7 mm/s, while most researchers report significantly higher values.

A review of the influence of environmental loads on cracks revealed temperature and humidity have the greatest influence. Changes in crack width caused by seasonal effects were reported up to 120 times greater than the effects of a 4.3-mm/s ground vibration while a 100-km/h wind speed was equated to a PCV = 33 mm/s. Structural response due to ordinary occupant loads was reported to be significantly greater than permissible vibration levels although structural response was more localized.

Common mechanisms causing variations in soil moisture leading to shrink/swell behavior of expansive soils have been reviewed. Rainfall has been identified as the key contributor to soil moisture variation with periods of drought coinciding with marked increases in cases of subsidence-related damage. Other factors such as vegetation, leaking services, and poor site drainage are important contributors and in the presence of expansive soils may significantly contribute to the cost of house maintenance.

The desiccating effect of tree root activity has been described as opportunistic and does not prescribe to rules related to canopy height and width. The zone of influence extends horizontally beyond the root network and causes an increase in the depth of seasonal drying by up 10 m. The depth of root penetration is dependent on species, soil permeability, and availability of moisture. Basic "safe" proximity rules for tree locations near structures remain problematic owing to the myriad factors influencing soil movement and meaningful rules are yet to be established, especially in semiarid environments. Smaller shrubs may also be responsible for highly localized desiccation.

The current trend toward smaller allotments and larger houses and the desire to have vegetation of appreciable size is placing a greater demand on house footings. In the event of tree-related subsidence damage, careful consideration of the appropriate course of action is necessary to ensure further damage is not sustained as a result of improper action such as tree removal. Periodic crown reduction and/or root trimming, installation of deep root barriers, or tree removal may control water demand of trees.

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